

Soil organic matter in a ponderosa pine forest with varying seasons and intervals of prescribed burn

J.A. Hatten^{a,*}, D. Zabowski^b, A. Ogden^b, W. Thies^c

^a Oregon State University, College of Oceanic and Atmospheric Sciences, 104 COAS Admin Building, Corvallis, OR 97331, USA

^b University of Washington, College of Forest Resources, Box 352100, Seattle, WA 98195-2100, USA

^c USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, OR 97331, USA

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Abstract

Prescribed burning is used to reduce fuel loads and return ponderosa pine forests of the Western U.S. to their historical structure and function. The impact of prescribed burning on soil is dependent on fire severity which is largely managed by burning in the fall or the spring; frequency of fire will also regulate long-term fire impacts. The objective of this study was to determine if soils and soil organic matter (SOM) were affected by prescribed burning in the fall or the spring using singular or multiple prescribed burns. Prescribed burning was initiated in the spring of 1997 and fall of 1997 at 5-year intervals and once during a 15-year period on a study site located within the Malheur National Forest of the southern Blue Mountains of eastern Oregon. Soils were sampled by major genetic horizon in 2004. The 5-year interval plots had burned twice with 1–2 years of recovery while the 15-year interval plots had burned only once with 6–7 years of recovery. Samples were analyzed for pH, carbon (C), nitrogen (N), C/N ratio, cation exchange capacity, base saturation, water repellency, and humic substance composition by alkali extraction. Fall burning decreased C and N capital of the soil (O horizon +30 cm depth mineral soil) by 22–25%. Prescribed burning did not have an effect on fulvic or humic acid C concentration (FA and HA, respectively) of the mineral soil and only a minor effect on FA and HA concentration of the O horizon. One or two fall burns decreased humin and the alkali non-soluble C (NS) content of O horizon by 15 and 30%, respectively. Initiating fall burning in fire-suppressed stands may not preserve soil C, N, humin, and NS content, but may replicate the natural fire regime. Spring burning using a return interval of 5 or more years reduces the fuel load while having little impact on soil C, N, and SOM composition and may be used to prepare a site for subsequent fall burns.

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1. Introduction

Ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws) forests in the inland Northwestern U.S. are fire adapted with fire-return intervals ranging from 7 to 38 years (Agee, 1994). Recent climate trends with fire exclusion and timber harvesting practices over the last 100 years have caused fuel loads to increase. This has resulted in frequent catastrophic wildfire, and shifts in the vegetative community (Tiedemann et al., 2000; Wright and Agee, 2004). Managers use prescribed burning to reduce fuel loads and return ecosystem structure and function to a historical set point. The impact to the ecosystem caused by this restoration process is dependent on the severity of the

prescribed fire, which is primarily managed by burning in either the fall or spring.

Historically, fires burned through these forests during the summer when fuels were dry, but frequent burning limited fuels resulting in low-severity fires (Agee, 1993). Prescribed burning is rarely conducted during the summer due to dry fuel conditions which causes fires to burn at a high severity; combined with the low likelihood of summer precipitation results in a difficult situation for fire control. For these reasons prescribed fires in ponderosa pine forests are frequently ignited during the spring or during the fall when fuel moisture is high and the probability of fire extinguishing precipitation is higher. Fall burning can be of moderate to high severity since the fuels have dried during the summer months and may represent the natural fire severity better than the low-severity spring burning. Fall burning may have a larger impact on accumulated fuels, but the current high fuel load may result in higher fire severity,

* Corresponding author. Tel.: +1 541 737 8273; fax: +1 541 737 2064.

E-mail address: jhatten@coas.oregonstate.edu (J.A. Hatten).

which may be detrimental to management goals of preserving and restoring vegetation or soil processes. Very few studies have characterized the difference between spring and fall burning on ecosystem components, especially soils.

Multiple treatments of prescribed fire may be necessary to obtain the desired forest conditions especially if the burn applications are low severity. The frequency with which fires are applied will determine if fire-induced changes accumulate or if the forest is able to recover between burn applications. The interaction of frequency and intensity may achieve some desired outcomes such as fuel reduction, but may cause cumulative impacts on soil nutrients and soil organic matter (SOM), potentially impacting forest productivity.

Soil organic matter includes both humic and non-humic organic substances associated with organic and mineral soil. Non-humic substances are generally any materials that can be identified and classified. Humic substances are refractory, dark colored, heterogeneous, organic compounds, produced as byproducts of microbial metabolism (Stevenson, 1994).

Classes of SOM have been operationally defined by an alkaline extraction and subsequent solubility under acidic conditions. Humin is composed of the largest molecules that have the greatest degree of aromaticity and the lowest concentration of oxygen (Stevenson, 1994). Humin is often associated with mineral surfaces, is very stable in the soil, and is not alkaline extractable. Non-soluble (NS) materials in O horizons, analogous to humin in the mineral soil, are usually made up of recognizable cellulose and lignin. Humic acid (HA) is soluble in alkaline conditions but precipitates in subsequent acidic solution and is relatively immobile in soils. Fulvic acid (FA) is soluble in both alkaline extract and in a subsequent acidic solution.

Black carbon (BC) is another component of SOM that is often included in the insoluble humin fraction of both O and mineral soil horizons. Black carbon is the heterogeneous, aromatic, and carbon-rich residue of biomass burning and fossil-fuel combustion; it includes charcoal, soot, and graphite (Goldberg, 1985). Charcoal is often part of the ash and residue remaining after biomass burning. Soot particles form in the gaseous phase and are easily transported from a fire site in the smoke plume. Graphite is usually geologically formed and inherited by soil. Black carbon decomposes at a much slower rate than uncharred material and has been suggested as a form of C useful for sequestering C in soil (Shneour, 1966; Kuhlbusch and Crutzen, 1995).

The effect of fire on soils is largely through the alteration and combustion of SOM, which can provide much of a soil's cation exchange capacity (CEC) and contains the majority of soil N capital (Stevenson, 1994). Combustion and volatilization may result in losses of SOM and may also mineralize organically bound elements such as N, P, and base cations, which are then available for uptake by plants or leaching from the soil (DeBano et al., 1998). Residual unburned SOM altered by heating is left with disproportionate losses of hydrogen and oxygen relative to C and increased aromaticity (Almendros et al., 1990; Baldock and Smernik, 2002; Almendros et al., 2003; Gonzalez-Vila and Almendros, 2003; Gonzalez-Perez

et al., 2004; Knicker et al., 2005). Increasing heating severity on SOM has been shown to decrease the oxygen content, thereby reducing FA and HA fractions while increasing aromaticity and humin content (Almendros et al., 1990; Fernandez et al., 1997, 2001, 2004). The shift of SOM to these recalcitrant materials has been shown to limit nutrients to organisms (Guinto et al., 1999). Few studies have examined the effect of varying fire severity in a natural setting on soils and SOM, especially in terms of season of prescribed burning.

A season of burn and burn interval study was begun in the southern Blue Mountains of eastern Oregon in 1997. This study provided an opportunity to examine the season of prescribed burn and repeated burn effects on soil and SOM. The objectives of this study were to: (1) determine the changes in soil chemical characteristics including SOM pools that result from difference types and number of prescribed burns and (2) quantify changes to total soil C and N capitals. This research is important to clarify processes that are controlling SOM quantity and quality and develop management recommendations for prescribed fire that protect soil quality.

2. Materials and methods

2.1. Site characteristics

The study site was located within the Malheur National Forest of the southern Blue Mountains of eastern Oregon (43°52'41"N/118°46'19"W). Elevation ranged from 1585 to 1815 m. Ponderosa pine is the dominant tree with some western juniper (*Juniperus occidentalis* Hook.) and curl-leaf mountain mahogany (*Cercocarpus ledifolius* Nutt.) in areas that have shallow soils. The ponderosa pine trees are predominantly between 80 and 100 years old; the sites were thinned in either 1994 or 1995. Kerns et al. (2006) found that grasses and sedges that dominate the understory include Idaho fescue (*Festuca idahoensis* Elmer), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve), sedges (*Carex* spp.), bottlebrush squirreltail (*Elymus elymoides* (Raf.) Swezey), basin wild rye (*Leymus cinereus* (Scribn. & Merr.) A. Löve), California Brome (*Bromus carinatus* Hook. & Arn), and western needlegrass (*Achnatherum occidentale* (Thurb.) Barkworth). Herbaceous cover consists of parsnipflower buckwheat (*Eriogonum heracleoides* Nuttall.), and large flowered collomia (*Collomia grandiflora* Douglas Ex Lindl.). Shrub cover is dominated by sage brush (*Artemisia tridentata* Nutt.), Oregon grape (*Mahonia repens* (Lindl.) G. Don), and rabbitbrush (*Chrysothamnus* Nutt. Spp.).

Parent materials of the study sites consist of basalt, andesite, rhyolite, tuffaceous interflow, altered tuffs, and breccia (Carlson, 1974). In addition, the soil has received ash from pre-historic eruptions of ancient Mount Mazama and other volcanos in the Cascade Mountains to the west (Powers and Wilcox, 1964). Carlson (1974) found Lithic Argixerolls, Lithic Haploxerolls, and Vertic Argixerolls within the research sites, which were confirmed during this study. Mollic Haploxeralfs, Humic Haploxerepts, and Typic Haploxerepts were also found during the soil sampling phase of the study.

At the Rock Spring SNOTEL station (44°N/118°50'W, 1603 m elevation), about 25 km WNW of the study site, annual precipitation averages 46 cm with 80% falling as snow between November and April (NRCS, 2007). Summers are dry and hot (17 °C mean air temperature in July–August) with cold winters (−3 °C mean air temperature in December–February).

2.2. Experimental design and treatment description

Six replicate study blocks were established and divided into three plots of similar stand type, aspect, slope, and parent materials (described by Thies et al., 2006a). Plot boundaries were established along roads and topographic features to control the prescribed burns. Each plot was randomly assigned as control, fall, or spring burn treatment. A burn interval of 5 or 15 years was assigned to a randomly designated half of each season's plot. The five treatment plots were of similar size (ranging from 6 to 13 ha) within each block.

Fires were ignited by hand-carried drip torches using a multiple-strip head-fire pattern. Flame lengths were maintained at 60 cm during all burns. Fall burns were initiated in October 1997 and reburned in 2002. Spring burns were initiated in June 1998 and reburned in 2003. Temperature, humidity, and wind speed and direction were similar during the application of all burns. At the time of soil sampling (summer of 2004), the 5-year interval plots had burned twice with 1–2 years of recovery while the 15-year interval plots had burned only once with 6–7 years of recovery.

2.3. Soil sampling

A transect of 8 points with 50 or 100 m spacing (depending on size of the particular plot) was established in each plot. Starting points and bearing were randomly chosen. Aspect, slope, and geomorphic shape were recorded at each point. Canopy cover was measured by estimating the amount of sky reflected off of a convex mirror held at chest level. A 4 m² plot was used to characterize vegetative and bare ground coverage at each sample point. Ground cover estimates of coarse woody debris (CWD), bare ground, grass, forbs, shrubs, and eroded soil were made. Burn severity was classified as low, moderate, or high at each point using a method adapted from Key and Benson (2006) by examining char height on trees, tree mortality, organic matter consumption, and presence of char. A low-severity fire would produce char heights less than 2 m on a tree bole and consumed little of the O horizon. Moderate-severity fires produce char heights between 2 and 4 m and left a thin layer of char on the surface of the soil. High-severity fire was designated when tree mortality was high and little O horizon remained.

Representative soils were sampled from every major genetic horizon to a depth of 30 cm at each sampling point. Bulk density samples of each mineral soil horizon were collected using a hammer corer or, when soils were rocky, by water displacement (Blake and Hartge, 1986). Mineral soil bulk density samples were brought back to the lab and oven dried at 105 °C until constant weight was achieved. Bulk density samples of the O horizon were sampled by removing a known

area (207 cm²), and averaging depth at 4 locations to obtain a volume. O horizon bulk density samples were oven dried at 70 °C until a constant weight was achieved. Water repellency of the surface of the mineral soil was measured in the field by dropping 0.5 ml water and measuring the amount of time needed for the droplet to completely infiltrate the soil (Krammes and DeBano, 1965).

2.4. Soil analysis

Soil samples were air-dried, weighed, and mineral horizons were separated into coarse and fine fractions with a 2 mm sieve. Coarse fractions were weighed to determine gravel and rock content. Subsamples from each air-dried mineral and O horizon were analyzed for pH using the saturated-paste method (Van Miegroet et al., 1994). Each O horizon sample and each fine fraction of every mineral soil sample was ground using a mortar and pestle for analysis of C and N on a Perkin Elmer 2400 CHN analyzer (Nelson and Sommers, 1996). Total soil C and N content were calculated on a per hectare basis for all horizons to a depth of 30 cm using C and N concentrations and total amount of coarse-content-free soil (<2 mm).

Samples were combined by horizon across grid points so that there was one composite O and A horizon per plot. Composite samples were analyzed for SOM composition, C, N, cation exchange capacity (CEC), and base saturation (%BS). Subsamples of each composite were homogenized using a small grinder. Base cations were extracted from a 5 g subsample of each composite A horizon samples using 50 ml of 1 M unbuffered NH₄Cl and extracted using a syringe extractor for 12 h (Skinner et al., 2001). Extract solution cation concentrations were determined using a Jarrell Ash Atomcomp Inductively Coupled Argon Plasma–Atomic Emission Spectrophotometer. Cation exchange capacity was calculated using the sum of exchangeable Al, Ca, Fe, H, K, Mg, and Na cations (meq 100 g^{−1} soil).

Soil organic matter was extracted from both O and A horizon composites using a method adapted from Schnitzer (1982). The extraction consisted of 100 ml of 0.1 N NaOH solution and either 10 g of mineral or 1 g of O horizon under N₂. Soil and extractant were placed into a 250 ml centrifuge bottle and shaken for 16 h on a reciprocal shaker. The solution was separated from the residue using a centrifuge at a force of 6635 × g for 10 min. The residue contained either humin and mineral material from the A horizons or non-soluble (NS) organic material (e.g., lignin and cellulose) from the O horizons. The supernatant solution and one rinse containing fulvic acid (FA) and humic acid (HA) fractions were collected for further processing. Humin or NS fractions were dried in a convection oven at 50 °C, weighed, prepared for C, H, and N analysis.

The supernatant containing FA and HA was acidified to pH 1 using 6 N HCl and allowed to stand overnight to precipitate HA. Fulvic acid was separated from HA by centrifugation at a force of 6635 × g for 10 min. Humic acid was freeze dried in a bench top lyophilizer, weighed, and stored in a light-protected dessicator.

The samples containing FA were purified to remove base-extracted acid-soluble non-humic materials and salts using a method adapted from Swift (1996). The solution containing FA was passed through a column containing 60 ml of DAX-8 resin (Supelco Supelite™ DAX-8; methyl methacrylate ester). The column was rinsed with 2 bed-volumes of deionized H₂O, and then eluted with 2 bed-volumes of 0.1 N NaOH. The eluate containing FA was collected and passed over a column containing Dowex H⁺ exchange resin to remove Na⁺. The solution containing FA was freeze dried, weighed, and stored in a light-protected dessicator. Prior to C, H, and N analysis, FA and HA samples were placed in pre-weighed tins and dried at 50 °C for 48 h. Fulvic acid and HA subsamples were analyzed for C, H, and N concentration.

2.5. Black carbon

Composited O and A horizons were analyzed for BC and black nitrogen (BN) using a method adapted from the CTO375 method outlined by Gustafsson et al. (1997). This method uses the ability of BC to resist thermal oxidation at 375 °C. This method may artificially create BC if conditions in the combustion process are anoxic, thereby promoting pyrolysis. During this study it was determined that less than 1.0 and 0.1 g of A and O horizons placed in ceramic crucibles (35 mm diameter) prevented charring. These samples were weighed to 0.1 mg and then into a preheated muffle-furnace (375 °C). After 20 h the samples were removed and weighed. Samples were placed into a muffle-furnace preheated to 550 °C for loss on ignition to determine the amount of LOI_{375–550} which would potentially contain BC and BN using the following equation:

$$\frac{\text{LOI}_{375-550}(\text{g})}{S_i(\text{kg})} = \frac{(A_{375}(\text{g}) - A_{550}(\text{g}))}{S_i(\text{g})} \times 1000 \text{ g/kg} \quad (1)$$

where *A* is ash or residue after heating at 375 or 550 °C, and *S_i* is the initial amount of soil.

The mass lost between muffle-furnace temperatures of 375 and 550 °C had a significant relationship ($p < 0.001$) with BC with r^2 values of 0.88 and 0.95 for seven selected O and seven selected A horizon samples, respectively. About half ($51 \pm 20\%$ (95% CI)) of LOI_{375–550} from the O horizons was found to be BC while only $10\% \pm 2\%$ (95% CI) of LOI_{375–550} from the A horizons was found to be BC. The O horizon ratio agrees with the recommendation by Nelson and Sommers (1996) to use a factor of 50% to convert SOM content of surface soils to C content. The low ratio calculated for A horizons may be the result of dehydration of mineral materials between muffle-furnace temperatures 375 and 550 °C which were not present in the O horizon. Black nitrogen accounted for $2.6 \pm 1.7\%$ (95% CI) and $1.1 \pm 0.2\%$ of LOI_{375–550} for O and A horizons, respectively. All samples were analyzed for LOI_{375–550} so these data were used to assess statistical differences among the burn treatments. The mass lost between 375 and 550 °C converted to BC or BN was compared to other research regarding BC and BN.

Using this method, Vertisol and Mollisol BC standards from Australia were both found to have a BC concentration of 1.5 and 0.9 g kg^{−1} soil, respectively. During the BC Ring Trial conducted by the Black Carbon Steering Committee (BCSC) these soils were found to have very low BC concentrations of 0.8 ± 0.4 (95% CI) and 0.8 ± 0.5 (95% CI) g kg^{−1} soil for the Vertisol and Mollisol, respectively, when tested by the CTO375 method (Hammes et al., 2007). The adapted method agrees with the BCSC results obtained for the Mollisol standard while slightly overestimating the BC concentration of the Vertisol standard; however, the overestimate is not appreciable. Charred-grass and wood standards prepared according to Hammes et al. (2006) were found to have BC concentrations of 6.3 and 0.7 g kg^{−1} sample, respectively, using the method described above. During the BC Ring Trial, these organic samples were found to have BC concentrations of 9.0 ± 7.0 (95% CI) soil and 0.0 ± 0.0 g kg^{−1} soil for the grass and wood samples, respectively (Karen Hammes, unpublished data). Thus, the adapted method agreed well with the results obtained for the organic samples.

2.6. Statistical analysis

Average values for each horizon were calculated for each treatment within each study block (6 replicates), $N = 30$ for each horizon. The experimental design was treated as a completely randomized block 2 by 2 factorial (season and interval of burn) with an augmented control. Differences between the soil and site characteristics from the control, 2 fall burns, 1 fall burn, 2 spring burns, and 1 spring burn were tested using a one factor ANOVA. Tukey's HSD was used to delineate significant homogenous subsets among the 5 treatments. Orthogonal contrasts were conducted to determine if season, number of burns, or the interaction of the two created significant differences within the 2 by 2 factorial of season and interval of burn. A significance level of $\alpha = 0.1$ was used for all statistical tests.

3. Results

3.1. Site and soil characteristics

Prescribed fire applied in the fall imparted a slightly higher estimated severity than spring burns (Table 1). Canopy cover was lowest on the fall burn plots partly as a result of higher tree mortality after the initial burn as reported by Thies et al. (2005, 2006b). Additionally, Thies et al. (2006a) found that after the second fall and spring burn woody fuels were reduced by 85 and 75%, respectively, relative to the control. The greatest reduction in woody fuels was caused by fall burning and highest tree mortality occurred after the initial fall burn, suggesting that the initial fall burns were the most severe.

It appears that burn severity is affecting the understory species composition and ground cover. Plots burned twice have reduced grass coverage relative to both controls and plots burned once. Fall burns had a slightly elevated coverage of forb species relative to spring burning ($p = 0.058$). Similarly, Kerns

Table 1

Surface cover (mean \pm standard deviation) of plots treated to 1 or 2 fall and spring burns ($n = 6$)

	Control	Fall		Spring		p	p_s	$p_{\#}$
		2	1	2	1			
Burn intensity	–	Low–moderate	Low–moderate	Low	Low			
CWD (%)	13 \pm 6 ^a	5 \pm 3 ^b	7 \pm 3 ^b	7 \pm 2 ^b	10 \pm 2 ^{ab}	0.014	0.205	0.124
Bare ground (%)	11 \pm 7 ^a	28 \pm 9 ^b	21 \pm 9 ^{ab}	22 \pm 12 ^{ab}	13 \pm 10 ^a	0.012	0.043	0.031
Grass (%)	11 \pm 8 ^{ab}	8 \pm 2 ^{ab}	14 \pm 8 ^b	5 \pm 3 ^a	11 \pm 7 ^{ab}	0.099	0.156	0.019
Canopy (%)	37 \pm 9 ^{bc}	24 \pm 8 ^a	25 \pm 9 ^{ab}	33 \pm 6 ^{abc}	41 \pm 8 ^a	0.006	0.001	0.142

Significant ($\alpha = 0.1$) differences are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s) and number of burns ($p_{\#}$). Interaction between season and number of burns was not significant. Letters indicate similar subsets (rows) using Tukey's HSD. CWD indicates coarse woody debris surface cover.

et al. (2006) found reduced grass cover after the initial spring burn and increased forb coverage after the initial fall burn. Percent bare ground increased after burning in the fall and spring and was highest on plots burned twice. This indicates increased erosion risk; however, water repellency of the mineral soil surface was significantly lower on the fall burn treatments possibly reducing erosion risk. There was a small significant ($p = 0.089$) increase in the percent of bare eroded soil on plots treated with two burns relative to plots with one burn (7 and 4%, respectively). The increased incidence of erosion could be reflecting a higher coverage of bare ground, allowing the evidence of erosion to be observed.

Two fall burns significantly lowered O horizon thickness 65% below the control (Table 2). The one fall and two spring burns reduced O horizon thicknesses by approximately 30% from the control but this reduction was not significantly different from the control. The thickness of the O horizon from plots treated to only one spring burn was not significantly different from the control.

Fall burn treatments had a lower O horizon C and N concentration than the spring burns, likely as a result of SOM consumption and higher ash content (Table 2). Neither the

season nor interval of burn treatments had a significant effect on A or B horizon C or N concentrations.

Summing O horizon and mineral soil total C to a 30 cm depth shows that fall burns reduced C by 22–25% relative to the spring and control treatments, while total N was reduced 13–19% (Fig. 1). Carbon loss with fall burning was driven by a statistically significant reduction of C from the O and A horizons, which were reduced by 62 and 11%, respectively, relative to the control (Table 3). Additionally, there is a reduction in C and N of the B horizons of plots burned 6–7 years ago which may be the result of a change in vegetative community or due to the random placement of the treatment plots onto soil types with B horizons that have less SOM.

3.2. Soil organic matter characteristics

Both O and A horizon total C was dominated by NS or humin materials (49 and 57%, respectively) (Table 5). The NS fraction of the O horizon had a much higher C:N ratio than the humin fraction of the A horizon, probably as a result of a higher concentration of unhumified and N-free materials such as cellulose and lignin (Tables 4 and 5). There was significantly

Table 2

Soil characteristics (mean \pm standard deviation) of O and A horizons in plots treated with 1 or 2 fall or spring burns ($n = 6$)

O Horizon	Control	Fall		Spring		p	p_s	$p_{\#}$	$p_{s\#}$
		2	1	2	1				
Thickness (cm)	3.7 \pm 1.2 ^a	1.3 \pm 0.4 ^b	2.6 \pm 1.3 ^{ab}	2.7 \pm 0.9 ^{ab}	3.9 \pm 0.8 ^a	0.001	0.002	0.005	0.992
pH	5.0 \pm 0.4 ^{ab}	5.3 \pm 0.3 ^c	5.3 \pm 0.2 ^{bc}	4.9 \pm 0.3 ^a	5.1 \pm 0.2 ^{abc}	0.004	0.001	0.657	0.151
C (g kg ⁻¹ soil)	456 \pm 53 ^{abc}	444 \pm 39 ^{ab}	438 \pm 48 ^a	484 \pm 34 ^{bc}	488 \pm 55 ^c	0.010	0.000	0.981	0.649
N (g kg ⁻¹ soil)	11.1 \pm 2.0 ^{ab}	9.9 \pm 1.1 ^a	10.0 \pm 1.2 ^a	11.4 \pm 1.8 ^b	11.9 \pm 1.8 ^b	0.042	0.003	0.546	0.706
C:N	53 \pm 9	57 \pm 8	56 \pm 9	55 \pm 13	53 \pm 10	0.684	0.286	0.471	0.857
A Horizon									
Water rep. (sec)	44 \pm 18 ^a	12 \pm 5 ^b	17 \pm 10 ^{ab}	40 \pm 26 ^a	38 \pm 32 ^{ab}	0.016	0.003	0.779	0.645
pH	6.0 \pm 0.2 ^{ab}	6.3 \pm 0.2 ^b	6.1 \pm 0.3 ^{ab}	5.9 \pm 0.2 ^a	6.2 \pm 0.1 ^{ab}	0.047	0.047	0.350	0.029
C (g kg ⁻¹ soil)	47 \pm 17	47 \pm 15	45 \pm 18	50 \pm 22	55 \pm 18	0.635	0.191	0.801	0.457
N (g kg ⁻¹ soil)	2.8 \pm 1.1	2.6 \pm 0.9	2.5 \pm 0.9	2.6 \pm 1.2	3.0 \pm 1.0	0.698	0.361	0.663	0.340
C:N	21 \pm 4	22 \pm 3	22 \pm 3	24 \pm 6	23 \pm 4	0.375	0.182	0.314	0.611
CEC (meq 100 g ⁻¹ soil)	22 \pm 6	22 \pm 3	20 \pm 6	21 \pm 5	24 \pm 4	0.522	0.506	0.921	0.114
%BS (%)	98.8 \pm 0.9	98.0 \pm 0.4	98.7 \pm 0.6	98.8 \pm 0.7	98.2 \pm 0.6	0.721	0.544	0.849	0.226
Ca (mg kg ⁻¹ soil)	3370 \pm 1030	3340 \pm 600	3020 \pm 1000	3110 \pm 910	3550 \pm 810	0.563	0.537	0.799	0.137

Significant ($\alpha = 0.1$) p -values are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s), number of burns ($p_{\#}$), and interaction of season and number of burns ($p_{s\#}$). Letters indicate similar subsets (rows) using Tukey's HSD. Abbreviations are: Water rep. = water repellency, CEC: cation exchange capacity, and % BS: base saturation.

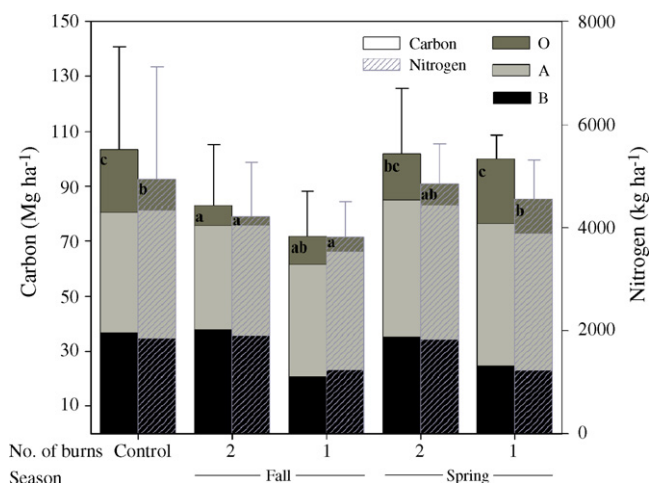


Fig. 1. Total C and N content in the top 30 cm of soil and O horizon after 1 or 2 fall and spring burns ($n = 6$). Error bars are 1 standard deviation from the mean total soil C or N content. Letters indicate similar groups of O horizon C or N content using Tukey's HSD.

higher concentration of NS C in the O horizons treated to two burns.

Fulvic acid was concentrated equally across both O and A horizons (3% of total C). The C:N ratio of FA from O horizons was very high (Tables 4 and 5) suggesting that there was a large quantity of N-free tannins or lignin decomposition products (e.g., vanillin) which may be included in the FA fraction (Qualls and Haines, 1991). Humic acid concentration of the A horizon was higher than the O horizon (23 and 9% of the total C, respectively) likely as a result of a higher degree of SOM humification.

Table 3

p -values for total carbon and nitrogen from O, A, B, and summed across all horizons (Fig. 1)

	p	p_s	$p_{\#}$	$p_{s*\#}$
Carbon				
O	0.000	0.000	0.059	0.448
A	0.218	0.024	0.593	0.953
B	0.112	0.603	0.027	0.324
Total carbon	0.077	0.021	0.330	0.750
Nitrogen				
O	0.001	0.000	0.040	0.335
A	0.714	0.183	0.703	0.865
B	0.332	0.918	0.062	0.719
Total nitrogen	0.349	0.188	0.298	0.912

Significant ($\alpha = 0.1$) p -values are in bold as determined by a one factor ANOVA and orthogonal contrasts for season (p_s), number of burns ($p_{\#}$), and interaction between season and number of burns ($p_{s*\#}$).

The consumption of O horizon by two fall burns is having the greatest impact on the NS, HA, and FA C and N content of the soils (Table 6). Similar reductions are found for BC and BN content of the O horizon (Table 7). Black carbon and nitrogen made up 6 and 14% of the total non-soluble materials (NS + humin), and was not significantly affected by the treatments ($p > 0.1$). The non-soluble materials, NS and humin, appear to be accumulating in the O and A horizons of the treatment with one spring burn while being consumed by multiple fall burns. Treatments with one spring burn are 6% higher than the control and 49% higher than plots with two fall burns.

Table 4

Soil organic matter characteristics (mean \pm standard deviation) of O horizons in plots treated with 1 or 2 fall and spring burns ($n = 6$)

O Horizon									
Control		Fall		Spring		p	p_s	$p_{\#}$	$p_{s* \#}$
		2	1	2	1				
C (g kg ⁻¹ soil)									
NS	222 ± 36	232 ± 40	213 ± 60	234 ± 34	225 ± 37	0.396	0.427	0.100	0.529
HA	40 ± 7 ^{ab}	36 ± 10 ^a	36 ± 9 ^a	42 ± 14 ^{ab}	50 ± 12 ^b	0.065	0.010	0.311	0.254
FA	13 ± 2	13 ± 4	10 ± 4	11 ± 2	12 ± 2	0.156	0.864	0.251	0.078
N (g kg ⁻¹ soil)									
NS	5.5 ± 0.9	5.9 ± 0.9	4.8 ± 1.4	5.6 ± 1.7	5.6 ± 1.6	0.651	0.188	0.651	0.592
HA	1.2 ± 0.3 ^{ab}	1.0 ± 0.3 ^a	1.1 ± 0.2 ^{ab}	1.3 ± 0.3 ^{ab}	1.6 ± 0.5 ^b	0.084	0.012	0.308	0.367
FA	0.17 ± 0.13	0.14 ± 0.12	0.10 ± 0.07	0.14 ± 0.04	0.12 ± 0.09	0.148	0.602	0.189	0.494
C:N									
NS	51.0 ± 5.6	56.1 ± 10	56.5 ± 13	55.7 ± 15	53.7 ± 16	0.843	0.685	0.836	0.769
HA	11.5 ± 1.5	11.4 ± 1.8	11.3 ± 2.0	11.8 ± 1.9	11.3 ± 1.0	0.946	0.650	0.742	0.557
FA	160 ± 127	238 ± 280	157 ± 98	104 ± 36	193 ± 176	0.318	0.282	0.930	0.067
C:H									
NS	2.1 ± 0.5	2.1 ± 0.9	1.8 ± 0.7	2.5 ± 1.6	1.5 ± 0.2	0.458	0.944	0.099	0.391
HA	2.8 ± 0.5	2.9 ± 0.6	2.8 ± 0.6	2.8 ± 0.5	2.8 ± 0.6	0.419	0.369	0.207	0.234
FA	0.89 ± 0.04 ^{ab}	0.94 ± 0.10 ^a	0.93 ± 0.10 ^{ab}	0.87 ± 0.09 ^{ab}	0.84 ± 0.07 ^b	0.061	0.005	0.527	0.608

Significant ($\alpha = 0.1$) p -values are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s), number of burns ($p_{\#}$), and interaction of season and number of burns ($p_{s*\#}$). Letters indicate similar subsets (rows) using Tukey's HSD. Abbreviations are: NS: non-soluble (O horizon); HA: humic acid; and FA: fulvic acid.

Table 5

Soil organic matter characteristics (mean \pm standard deviation) of A horizons in plots treated with 1 or 2 fall and spring burns ($n = 6$)

A Horizon									
Control		Fall		Spring		p	p_s	$p_{\#}$	$p_{s\#}$
		2	1	2	1				
C (g kg ⁻¹ soil)									
Hu	25 ± 8	26 ± 6	26 ± 10	27 ± 11	30 ± 7	0.592	0.303	0.472	0.513
HA	12 ± 5	11 ± 3	10 ± 5	11 ± 3	12 ± 4	0.769	0.522	0.706	0.323
FA	1.1 ± 0.3	1.3 ± 0.4	1.1 ± 0.4	1.0 ± 0.3	1.3 ± 0.6	0.364	0.871	0.518	0.060
N (g kg ⁻¹ soil)									
Hu	1.5 ± 0.7	1.4 ± 0.5	1.5 ± 0.6	1.4 ± 0.6	1.6 ± 0.6	0.879	0.654	0.442	0.565
HA	0.7 ± 0.3	0.6 ± 0.2	0.6 ± 0.2	0.6 ± 0.2	0.7 ± 0.2	0.617	0.499	0.923	0.406
FA	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.01	0.04 ± 0.02	0.555	0.713	0.409	0.241
C:N									
Hu	23.4 ± 10.2	23.1 ± 8.2	22.4 ± 5.5	25.2 ± 9.5	24.4 ± 8.0	0.788	0.240	0.662	0.970
HA	13.9 ± 1.5	13.8 ± 1.1	13.7 ± 2.7	13.9 ± 1.7	13.5 ± 1.8	0.668	0.671	0.940	0.595
FA	39.0 ± 13.8	44.4 ± 13.8	35.4 ± 6.9	42.3 ± 11.7	41.9 ± 8.3	0.622	0.676	0.584	0.677
C:H									
HA	1.44 ± 0.19	1.51 ± 0.18	1.53 ± 0.18	1.56 ± 0.33	1.53 ± 0.19	0.984	0.918	0.644	0.828
FA	1.01 ± 0.04 ^a	1.05 ± 0.06 ^{ab}	1.14 ± 0.12 ^b	1.01 ± 0.09 ^a	1.05 ± 0.09 ^{ab}	0.030	0.037	0.041	0.292

Significant ($\alpha = 0.1$) p -values are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s), number of burns ($p_{\#}$), and interaction of season and number of burns ($p_{s\#}$). Letters indicate similar subsets (rows) using Tukey's HSD. Abbreviations are: Hu: humin; HA: humic acid; and FA: fulvic acid.

4. Discussion

This study showed that C loss with multiple fall burns was driven by a statistically significant reduction of C from both the O and A horizons, while only minor changes were inflicted by burning in the spring. Changes to soil organic matter composition appears to be driven by consumption and transformation of the O horizon which may be influencing inputs to the A horizon.

The thickness of O horizon was reduced by 65% which was similar to other studies on prescribed burning in ponderosa pine forests that found a 42% reduction caused by spring prescribed burns (Choromanska and DeLuca, 2001) and 51% reduction caused by fall prescribed burns (Covington and Sackett, 1984). Fall burning at 5-year intervals may keep O horizon thickness thin and patchy, exposing mineral soil to erosion and reducing organic matter inputs to the mineral soil. The lower severity of the spring burns removed a smaller portion of O horizon and

Table 6

Total C and N by each soil organic matter fraction (mean \pm standard deviation) of O and A horizons in plots treated with 1 or 2 fall or spring burns ($n = 6$)

		Control	Fall		Spring		P	P_s	$P_{\#}$
			2	1	2	1			
Mg Carbon ha ⁻¹									
NS	O	13.8 ± 6.5	4.3 ± 1.0	7.1 ± 3.0	9.4 ± 3.1	14.3 ± 6.4	0.148	0.067	0.183
Humin	A	25.0 ± 9.4	22.9 ± 4.2	25.9 ± 11.2	28.7 ± 11.0	26.3 ± 5.1	0.787	0.341	0.926
	Sum	38.8 ± 13.7 ^{ab}	27.3 ± 4.0 ^a	33.0 ± 10.8 ^{ab}	38.0 ± 11.0 ^{ab}	40.6 ± 9.5 ^b	0.081	0.016	0.244
Humic acid	O	2.6 ± 1.4 ^{ab}	0.7 ± 0.2 ^a	1.2 ± 0.5 ^a	1.7 ± 0.7 ^{ab}	3.1 ± 1.2 ^b	0.023	0.014	0.061
	A	11.8 ± 5.3	9.7 ± 2.6	10.2 ± 4.8	11.4 ± 3.8	10.4 ± 2.8	0.805	0.496	0.859
Fulvic acid	O	0.8 ± 0.4 ^{bc}	0.2 ± 0.1 ^a	0.3 ± 0.1 ^{ab}	0.4 ± 0.1 ^{abc}	0.7 ± 0.2 ^c	0.014	0.024	0.105
	A	1.1 ± 0.4	1.1 ± 0.4	1.1 ± 0.4	1.1 ± 0.5	1.2 ± 0.6	0.991	0.833	0.960
kg Nitrogen ha ⁻¹									
NS	O	355 ± 195 ^{ab}	99 ± 32 ^a	171 ± 93 ^{ab}	230 ± 114 ^{ab}	358 ± 152 ^b	0.051	0.028	0.140
Humin	A	1520 ± 783	1271 ± 434	1467 ± 720	1527 ± 599	1413 ± 501	0.830	0.568	0.816
Humic acid	O	82 ± 51	20 ± 9	36 ± 16	51 ± 20	97 ± 46	0.760	0.424	0.503
	A	709 ± 318	547 ± 162	562 ± 252	635 ± 168	572 ± 144	0.546	0.525	0.757
Fulvic acid	O	9 ± 7 ^a	3 ± 3 ^b	3 ± 2 ^b	5 ± 2 ^{ab}	7 ± 6 ^a	0.004	0.008	0.444
	A	38 ± 18	34 ± 18	30 ± 26	32 ± 12	34 ± 19	0.903	0.864	0.918

Significant ($\alpha = 0.1$) differences are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s), and number of burns ($p_{\#}$). Letters indicate similar subsets (rows) using Tukey's HSD. Interaction between season and number of burns was not significant. Sum of HA and FA C and all fractions of N were not significantly different between the treatments and data not shown.

Table 7

Black carbon (BC) and black nitrogen (BN) content (mean \pm standard deviation) for O and A horizons in plots treated with 1 or 2 fall or spring burns ($n = 6$)

Control		Fall		Spring		p	p_s	$p_{\#}$
		2	1	2	1			
BC (Mg ha ⁻¹)								
O	0.12 ± 0.11 ^b	0.04 ± 0.02 ^a	0.07 ± 0.04 ^{ab}	0.08 ± 0.08 ^{ab}	0.13 ± 0.09 ^b	0.049	0.029	0.074
A	1.91 ± 0.59	1.90 ± 1.11	1.89 ± 0.96	2.10 ± 1.00	1.83 ± 0.76	0.953	0.786	0.589
BN (kg ha ⁻¹)								
O	6.0 ± 5.3 ^b	1.8 ± 1.0 ^a	3.6 ± 2.2 ^{ab}	4.2 ± 3.9 ^{ab}	6.6 ± 4.8 ^b	0.049	0.029	0.074
A	228 ± 71	227 ± 133	227 ± 114	251 ± 119	219 ± 91	0.953	0.786	0.589

Significant ($\alpha = 0.1$) *p*-values are in bold as determined by a one-factor ANOVA (*p*) and orthogonal contrasts for season (*p_s*), and number of burns (*p_#*). Interaction of season and number of burns was not significant. Letters indicate similar subsets (rows) using Tukey's HSD.

time since burning (6–7 years) has allowed O horizon depth to recover. Approximately 2.4 cm of O horizon has accumulated since the initial fall and spring burns, when O horizons were measured by Smith et al. (2004). The thickness of the O horizon on plots with one spring burn appears to have completely recovered sooner than plots with one fall burn. Ogden (2006) measured tree ring growth at the same time soils were sampled and reported that there was no significant treatment effect suggesting that there was no change to productivity and therefore inputs to the O horizon through litterfall. This evidence implies that more O horizon remained after spring burning relative to fall burning. Additionally, organic matter and nutrient inputs from the O horizon to the mineral soil are being maintained on the plots with one spring burn.

Fall burn treatments had a lower O horizon C and N concentration than the spring burns, likely as a result of SOM consumption and higher ash content (Table 2). Elevated pH values of O horizons from plots burned in the fall as a result of this ash content. Soil pH from plots with two spring burns may be influenced by a reduction in understory grass and grass litter leading to the significant interaction between season and number of burns on the A horizon pH.

Increasing fire frequency has been shown to decrease the concentration of C and N of the upper 5 cm of A horizon in an Arizona ponderosa pine forest (Neary et al., 2003). Mineral soil C and N concentration from the present study was unaffected by burning suggesting that the severity of the prescribed burns may be too low to cause significant differences in C concentration, the number of repeated burn applications is too low for changes to have accumulated, or that these soils are able to resist changes to C and N concentration.

Average A horizon C and N concentration was 49 g C kg⁻¹ soil and 2.7 g N kg⁻¹ soil with B horizon concentrations averaging 25 g C kg⁻¹ and 1.3 g N kg⁻¹ soil. Ponderosa pine stands in eastern Washington, eastern Oregon, and western Montana averaged 8–56 g C kg⁻¹ soil and 7–13 g C kg⁻¹ soil for A and B horizons, respectively (Monleon et al., 1997; Baird et al., 1999; DeLuca and Zouhar, 2000; Hatten et al., 2005). Nitrogen concentrations in these forests averaged 1.3–2.0 g N kg⁻¹ soil and 0.7–1.8 g N kg⁻¹ soil for A and B horizons, respectively. The highest values of C and N occurred under ponderosa pine stands in central Oregon (Monleon et al., 1997) and this study (eastern Oregon). These remarkably high C and N concentrations may be driven by the understory

vegetation of both eastern and central Oregon forests, which are dominated by grasses that could have increased the amount C and N through the incorporation of fine roots into the upper soil horizons. Additionally, andic materials may be promoting C and N accumulation in the soil through complexation of organic matter with allophanic mineral materials (Zunino et al., 1982a, 1982b).

Baird et al. (1999) found a total C content of 48 Mg ha⁻¹ in the upper 30 cm, including the O horizon, of an unburned ponderosa pine forest in eastern Washington. A high severity wildfire reduced C content to 30 Mg ha⁻¹ (a 37% reduction from control). Of the 18 Mg C ha⁻¹ lost due to wildfire 61% of the loss was caused by consumption of C directly from the A horizon, while B horizons were unaffected by burning. In the current study only 17% of the 26 Mg ha⁻¹ difference between the control and fall burns was due to reduced A horizon C content, with most C reduction caused by consumption of O horizon. The lower severity of fall prescribed burning relative to wildfire is helping to preserve C in the A horizon. Further, the high C content of the A horizon (44 Mg C ha⁻¹ in control A horizon) relative to Baird et al. (1999) (23 Mg ha⁻¹ in control A horizon) reduces the magnitude of change. Relative to wildfire, even the higher severity fall burning may protect soil C.

The removal of O horizon by burning may be reducing the water repellency of the surface of the mineral soil. Water repellency was significantly negatively correlated with bare ground coverage ($R = -0.612$; $p < 0.05$). Hydrophobic O horizon materials were removed by fire, thereby reducing inputs of hydrophobic materials into the mineral soil. Further, mycelia of fungi have been shown to promote hydrophobicity along with litter of certain plants (Doerr et al., 2000). Smith et al. (2004) found that the initial fall burns of these sites had significantly reduced live ectomycorrhizal root biomass and ectomycorrhizal fungi species richness in the surface 10 cm. The high-severity initial fall burn may have caused a decrease in hydrophobic compounds in both the O and A horizons and reduced the populations of fungal species that produce hydrophobic materials. Erosion was not significantly ($p > 0.1$) correlated with mineral soil water repellency suggesting that this change was caused by an affect on SOM composition.

Total humified materials (humin, HA, and FA) accounted for 60 and 83% of the C from O and A horizons, respectively. The remaining 40% and 17% may include soluble non-humic

materials, which would have been discarded during FA purification, or hydrophobic compounds not desorbed from the DAX-8 column during FA purification. These fractions have been shown to be influenced by fire severity in Hatten (2007); however, no significant ($p > 0.1$) treatment effect was detected on the proportion of unaccounted C. More research is necessary to determine what is causing the loss of water repellency on the fall burn plots.

The HA:FA ratio of the A horizon was unaffected by burning but is remarkably high (HA:FA = 11) for a forest soil as compared to HA:FA data presented by Kononova (1966). Fulvic acid preparation using DAX-8 resin may have reduced FA content and elevated the HA:FA ratio as reported by Kuwatsuka et al. (1992). If the portion of C removed by DAX-8 purification of FA is added to the FA fraction, the HA:FA ratio is 1.3 which is similar to the HA:FA ratio of other Mollisol soils (Kononova, 1966).

Knicker et al. (2005) found a decrease in HA and an increase in humin concentration 5 years after severe wildfire. High-severity wildfire may increase the recalcitrant C within the SOM pool for an extended period of time. However, Knicker et al. (2005) studied only one composite sample each from a burned and unburned area, which limits the conclusions from that study. The severity of the prescribed fires in the current study may not have been high enough to cause lasting changes to SOM. While low- and moderate-severity fires have been shown to affect SOM composition (Hatten, 2007), these changes do not persist through incubation, suggesting that spring and fall prescribed burning will not have long-lasting effect on SOM composition. High-severity fire, such as that studied by Knicker et al. (2005), may cause a long-term change to SOM composition by exceeding a threshold severity where the chemical reactions which create recalcitrant materials dominate.

The higher concentration of NS C in the O horizons treated to two burns is likely caused by charring. Charring may have increased the NS C:H ratio of the plots with the most recent burns having a C:H ratio above 2.0. Baldock and Smernik (2002) found that wood (C:H = 0.7) heated to temperatures above 250 °C had C:H ratios greater than 2.0 and Almendros et al. (2003) observed a similar response to the C:H ratio of heated peat. Hatten (2007) showed that NS C in the O horizon subjected to moderate- or high-intensity fire did not change after decomposition, suggesting that this charred material does not readily decompose. If charred NS C is not consumed by wildfire or another prescribed fire, then it may accumulate in the soil due to slower decomposition.

Even though the NS C concentration of O horizons from plots with two burns is higher the reduction of O horizon mass caused the fall burn plots to have the lowest recalcitrant (NS + humin) C content (Table 6). Repeated fall burning may be consuming material that contributes to humin and NS substances in both A and O horizons. The consumption of O horizon may be the most important factor regulating the quantity of long-term fire-affected SOM after repeated low-intensity prescribed fire. The reduction of NS materials caused by the fall burning at a 5-year interval may be further reduced

with future repeated burning and could affect soil processes such as CEC in addition to available nutrients and understory species reestablishment.

Czimczik et al. (2005) found that BC was non-existent in Scots pine (*Pinus sylvestris* L.) forests where the most recent fire was high severity. The charred material may have been present prior to burning; however, they hypothesize that it was consumed by the high-intensity fire. They suggest that a low rate of surface soil mixing did not incorporate BC into the mineral soil and thereby left it exposed to burning. However, other studies of Scots pine forests have found high levels of charcoal after high- and low-severity wildfire (e.g. Zackrisson et al., 1996). At the current study site, burrowing animals are prevalent and have been observed to mix mineral and organic horizons. Also, cattle are sometimes present in these forests and are able to churn organic material into the mineral soil. Mixing of charred NS material from the O horizon into the A horizon may increase total humin C content of the A horizon, which could protect this carbon from low- to moderate-severity fires in the future.

Non-soluble materials such as charcoal may be providing soils under fire-prone forests with materials which contribute to the total soil CEC. Liang et al. (2006) showed that charcoal incorporated into mineral soil can impart a higher CEC over time. The presence of charcoal along with a slightly higher pH in the A horizon of the plots with one spring burn to result in high CEC (Table 2).

The reduction of NS materials caused by the fall burning at a 5-year interval may be further reduced with future repeated burning and could affect soil processes such as CEC in addition to available nutrients and understory species reestablishment. Charcoal has been shown to reduce the inhibitory effect of allelopathic compounds on seedling establishment and nitrification (Zackrisson et al., 1996; Wardle et al., 1998; DeLuca et al., 2002, 2006). If the understory species of ponderosa pine forests are adapted to the presence of charcoal at the time of understory reestablishment after low-severity fire, then a fire regime that allows charcoal to accumulate may provide the most robust soil conditions for native plant restoration. The initial fall burn has caused a higher cover of non-native understory species (Kerns et al., 2006). If non-soluble materials in this study are dominated by charcoal then the higher-severity fall burning at 5-year intervals may reduce the success of understory native species reestablishment through the consumption of charcoal. The initial fall burn and fall burns at 5-year intervals may be consuming charcoal and other non-soluble materials that are important for soil processes, ecosystem function and C sequestration. High-severity fall burns applied every 5 years may not restore understory species composition to the historical structure.

The initial fall burns may have had the largest impact to the soil; however, they do not appear to have had a significant impact to soil processes or long-term productivity. There was no significant effect on CEC and %BS and only minor changes to soil pH. Additionally, Ogden (2006) examined available N and ring growth of the soils and trees, respectively, of this study and did not find a significant effect between the treatments. The

high OM content of these soils may be imparting resilience to these soils. A lower-productivity soil with less OM may not have as much capacity to resist change as well. Using fall burning to reintroduce fire to a forest with a lower quality soil could impact soil productivity by removing a greater percent of total of C and N.

Reinitiating fire into a fire-suppressed forest achieves management goals of fuel reduction whether the burns are applied in the fall or spring. However, increased SOM consumption of the fall burns may lead to significant changes to soil processes in these stands in the future. It is possible that the high SOM content of these soils gives them the capacity to resist major changes caused by the initial fall burning that a lower quality soil may yield. Using fall burns initially to reduce fuel loads may need to be avoided in order to preserve soil health and sequester C in fire-suppressed stands.

5. Conclusions

The reintroduction of fire after 100 years of suppression has had the intended result of reducing fuels in the form of O horizon and coarse woody debris (CWD). Burning was associated with elevated pH of both O and A horizons while fall burning decreased the hydrophobicity at the surface of the A. Higher-severity fall burns decreased the C and N capital of the O and A horizons while the spring burns did not significantly affect the total C and N content of the soil. Generally, the prescribed fire treatments had few effects on SOM composition. Soil organic matter of the O horizon was partly consumed by the prescribed fires, which was reflected in reduced NS, HA, and FA content. Recalcitrant materials appear to be accumulating in the O and A horizons of the treatment with one spring burn while being consumed by multiple fall burns with most of the impact appearing to have been caused by the initial fall burn. Reinitiating fire into a fire-suppressed forest using fall burning may reduce soil C and N and impact soil processes. Spring burning at longer than 5-year intervals may cause little to no impact to the soil with repeated burns. Therefore, lower-severity spring burning at greater than 5+ year intervals could be used to reduce fuels and forest structure before applying fall burns which may simulate the natural fire regime.

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